Orbital migration, pebble vs planetesimal accretion -- Implication for ARIEL--

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- Current status of planet formation theory
  - Type II migration -- jupiters
  - Type I migration – super-Earths
  - Pebble accretion
- Implication for ARIEL observation

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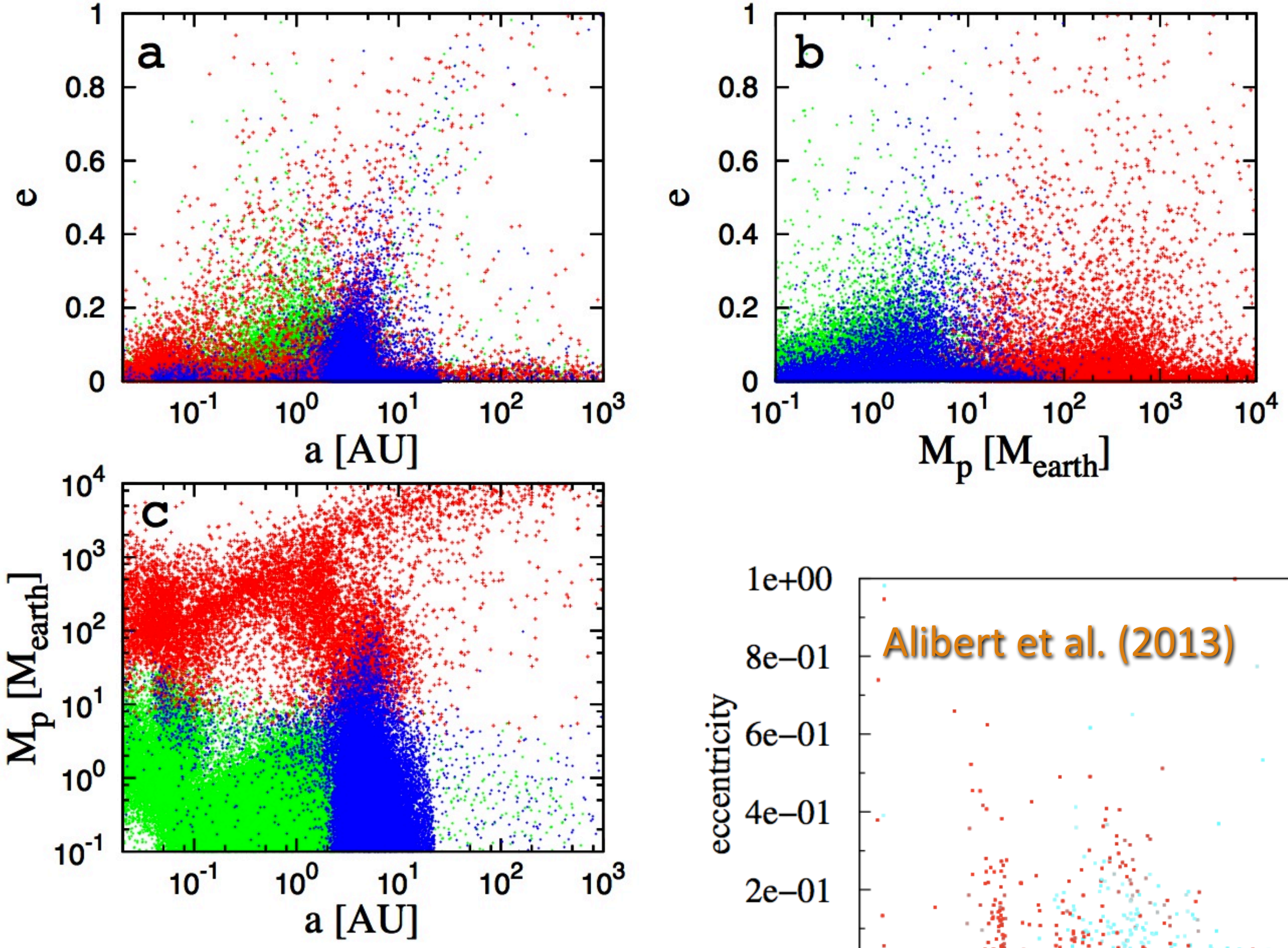
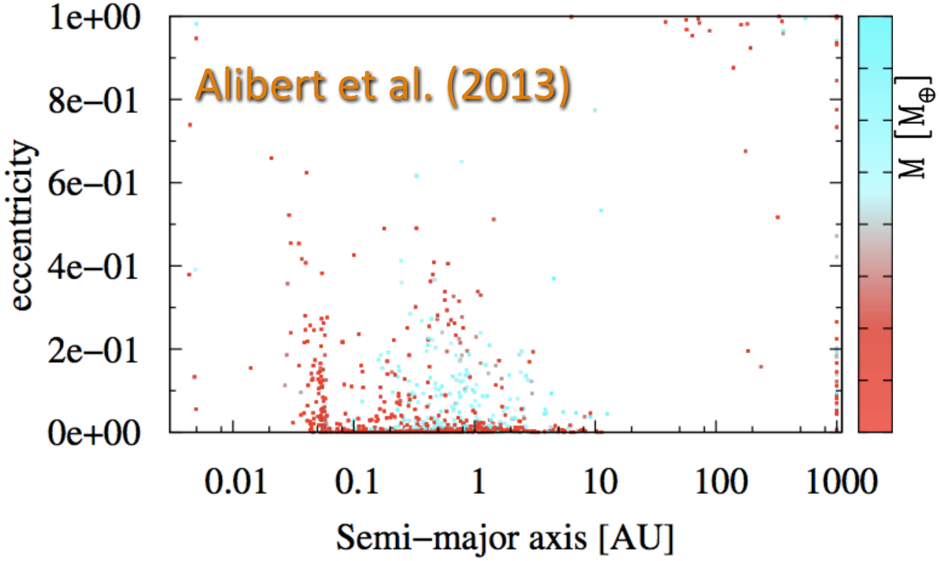
Planet Population Synthesis Simulations

Ida & Lin (2004a,b,05,08a,b,10), Ida+(2013), Mordasini+(2009a,b,12), Alibert+(2011,13)

based on planetesimal accretion

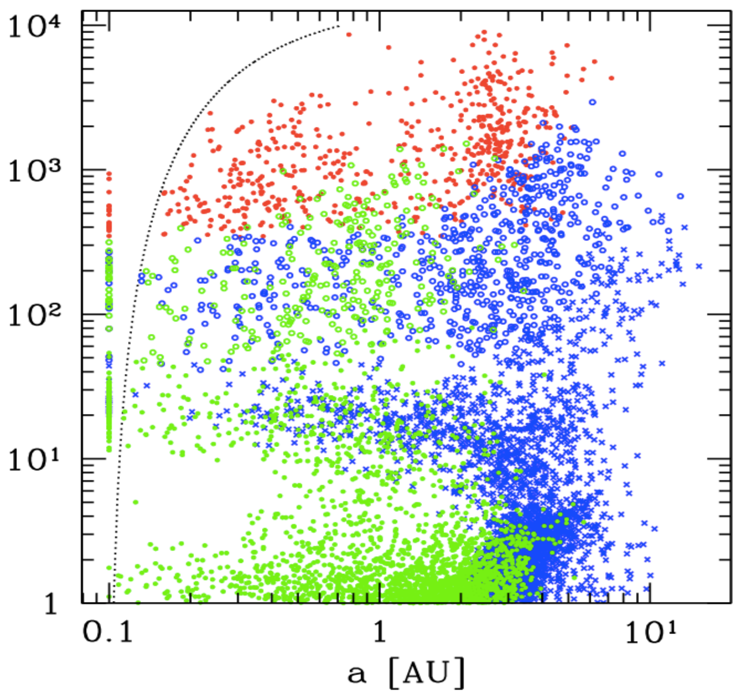


Ida et al. (2013)

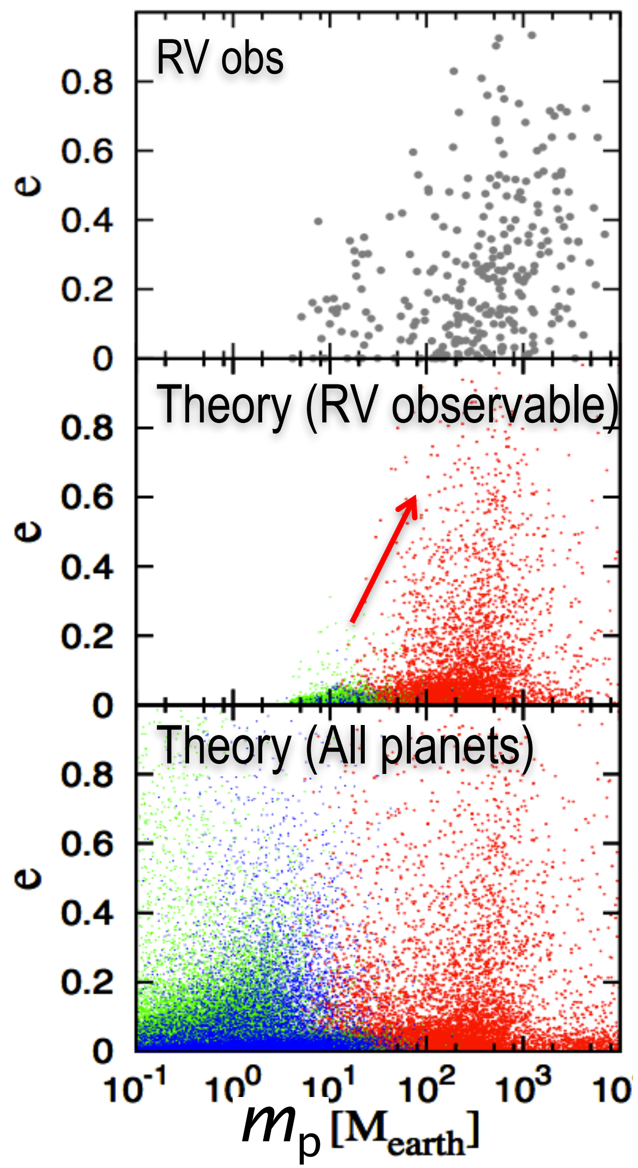


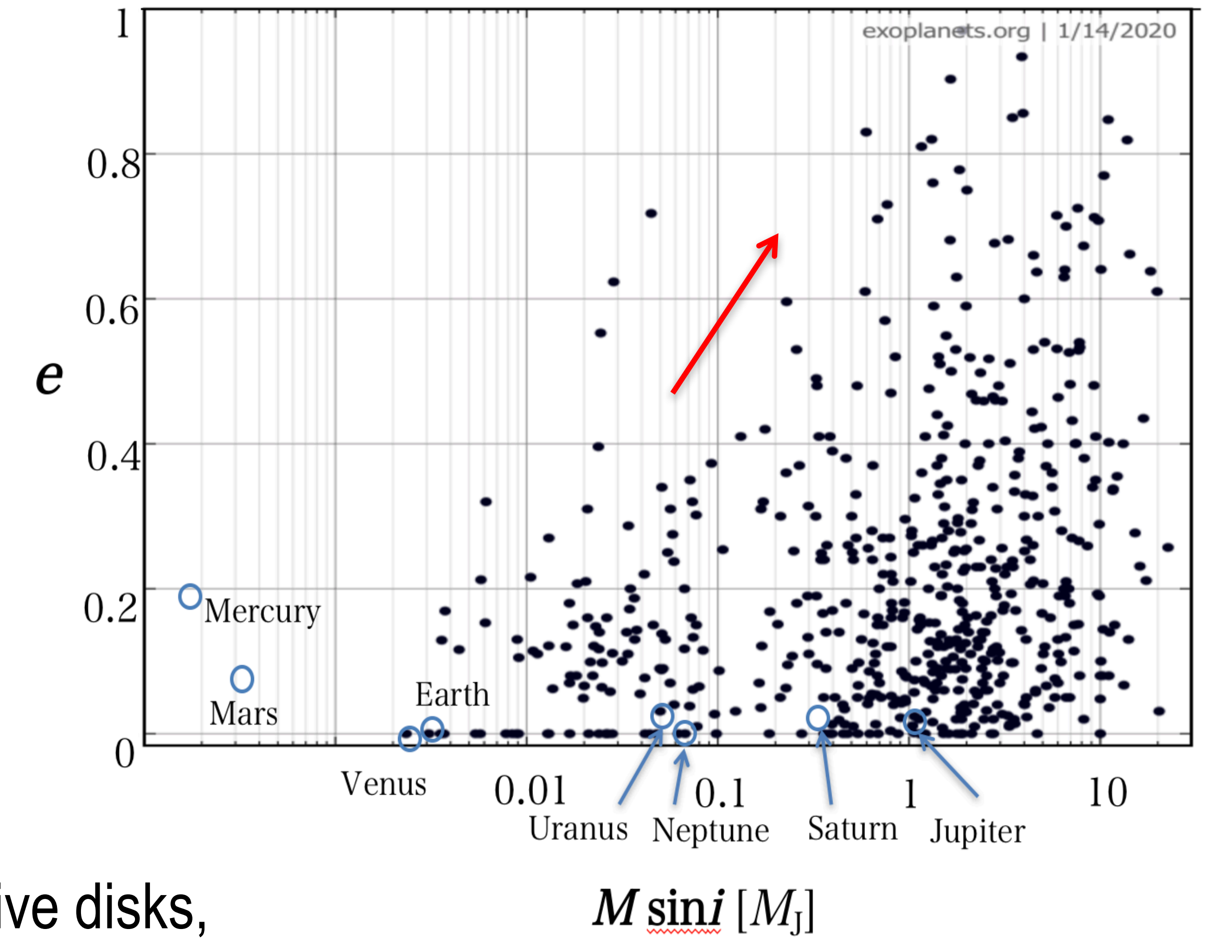
Alibert et al. (2013)

Mordasini et al. (2009a)



Observed *e-M* correlation : reproduced by planet-planet scattering





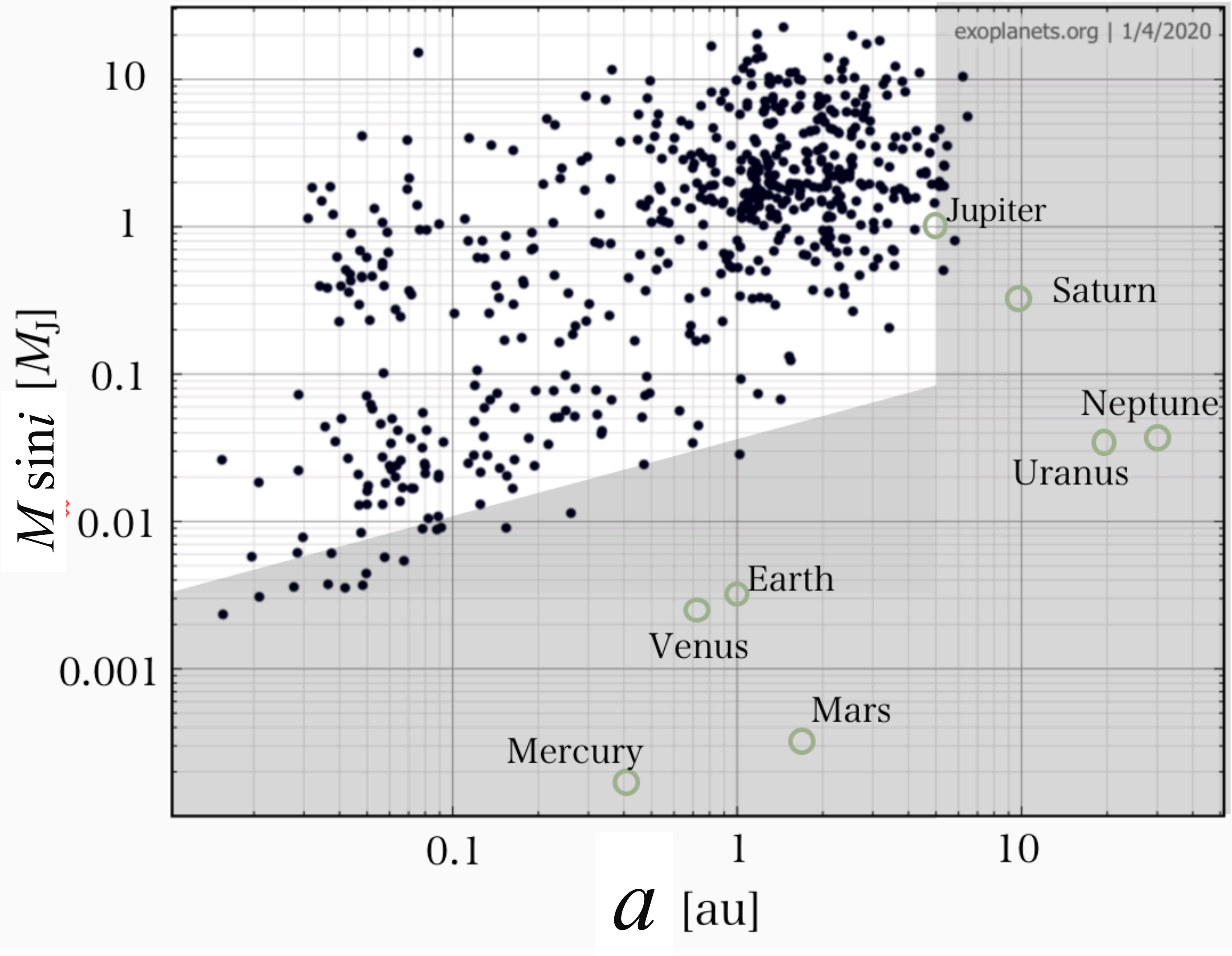
in massive disks,
- a few large giants
  → dynamical instability
  → strong scattering

Ida, Lin, Nagasawa (2013)

Observed *M-a* distribution : many difficulties

Planets discovered by RV surveys

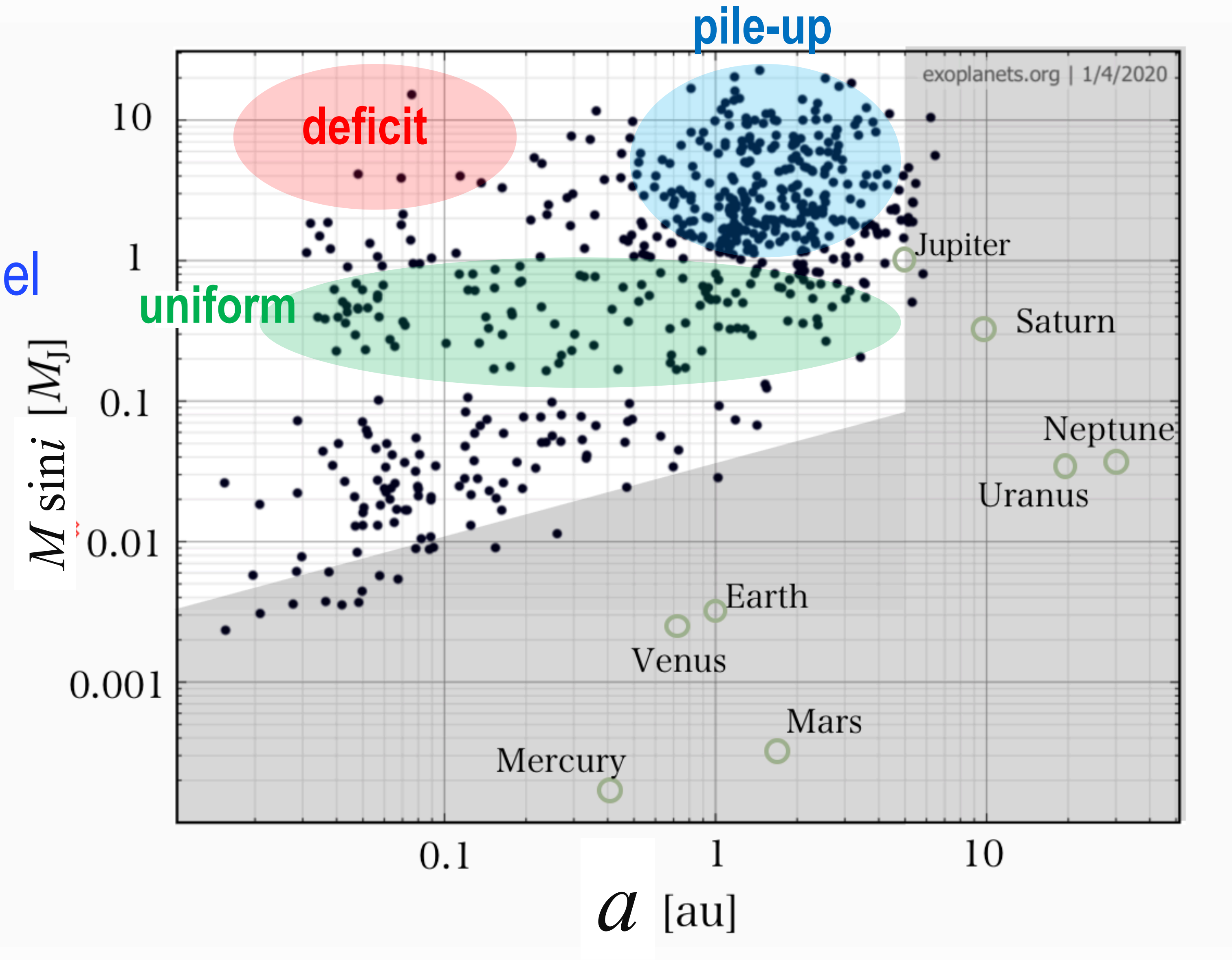
to avoid bias in a of transit surveys



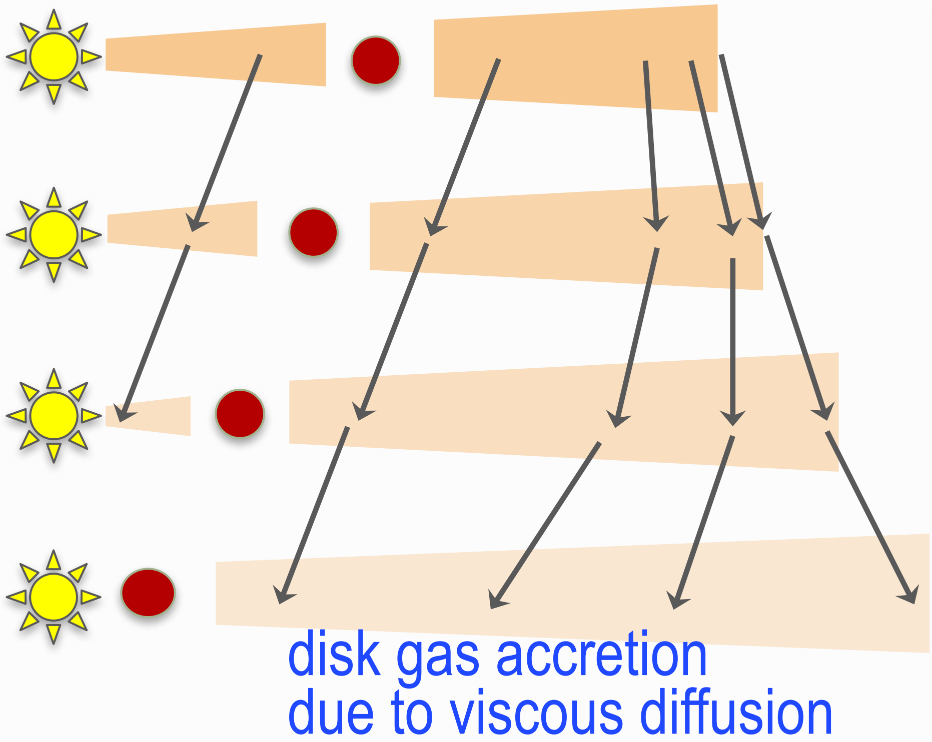
M-a distribution of jupiters

- $M > M_J$
  piled up at > 0.5 au
  inconsistent with
  classical type-II mig model

- $0.1\ M_J < M < M_J$
  log uniform in *a*



Type-II migration problem



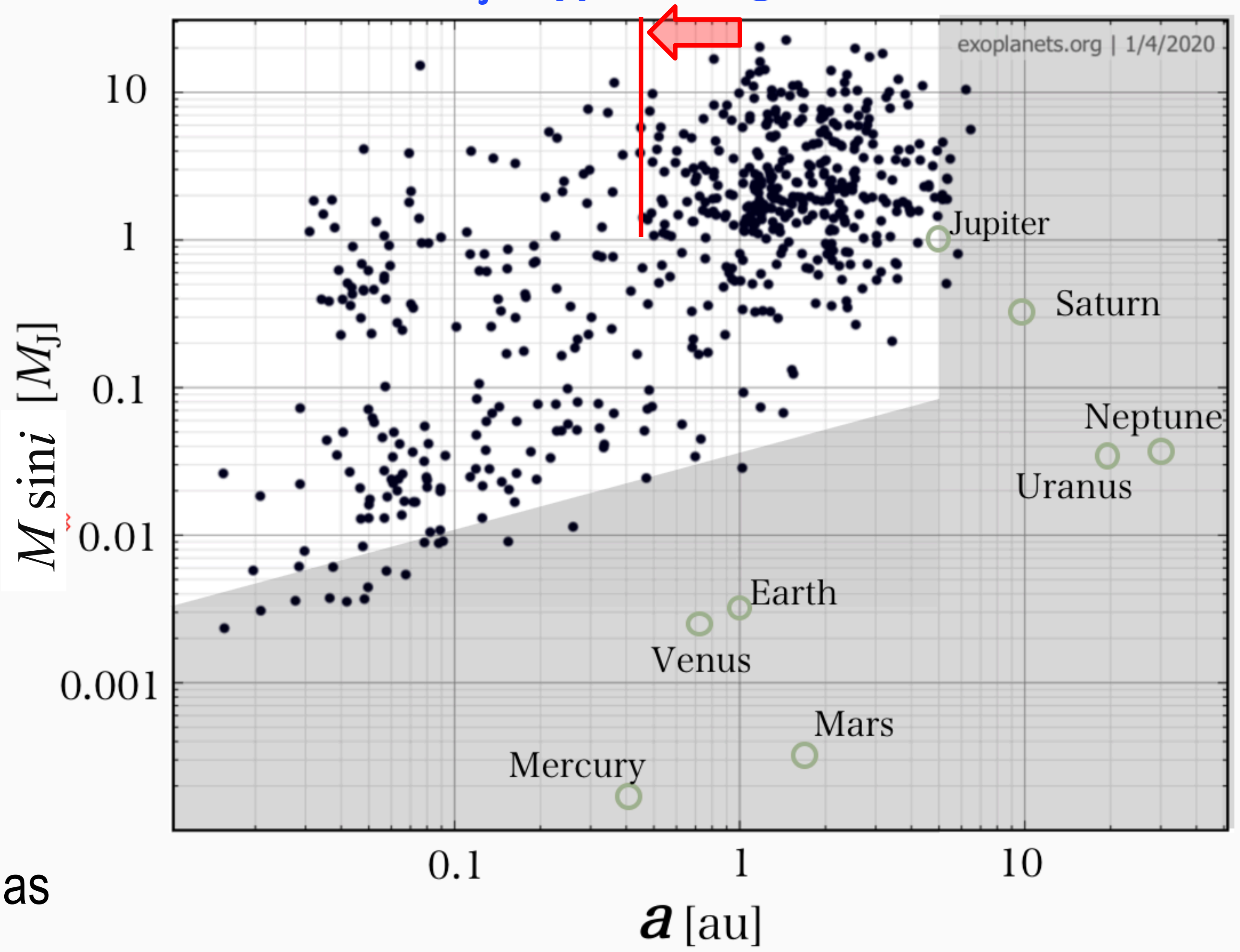
Classical idea: tied to disk accretion

Lin & Papaloizou (1986)

-- gap formation

-- migration to the inner cavity with disk gas

$M > M_J$: type-II migration: halted?



How to halt type II migration for sub-jupiters?

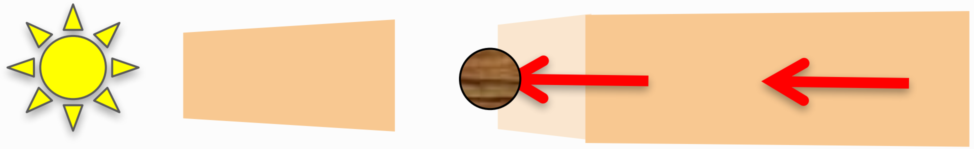
1. **Only low viscous α** -- does not work

2. **planetary growth by full disk gas accretion** even after gap formation

   Mordasini et al. 2009a, 2009b, Alibert et al. 2011, 2013

   → too much growth?

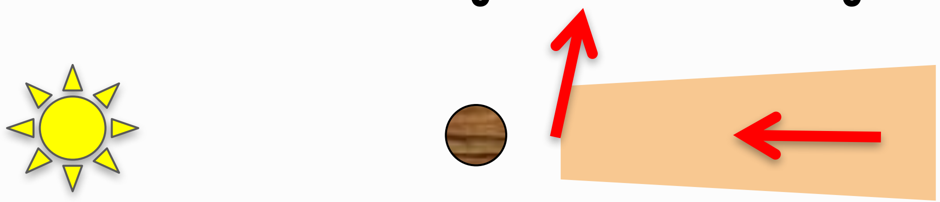
   → assume good **external photoevaporation**

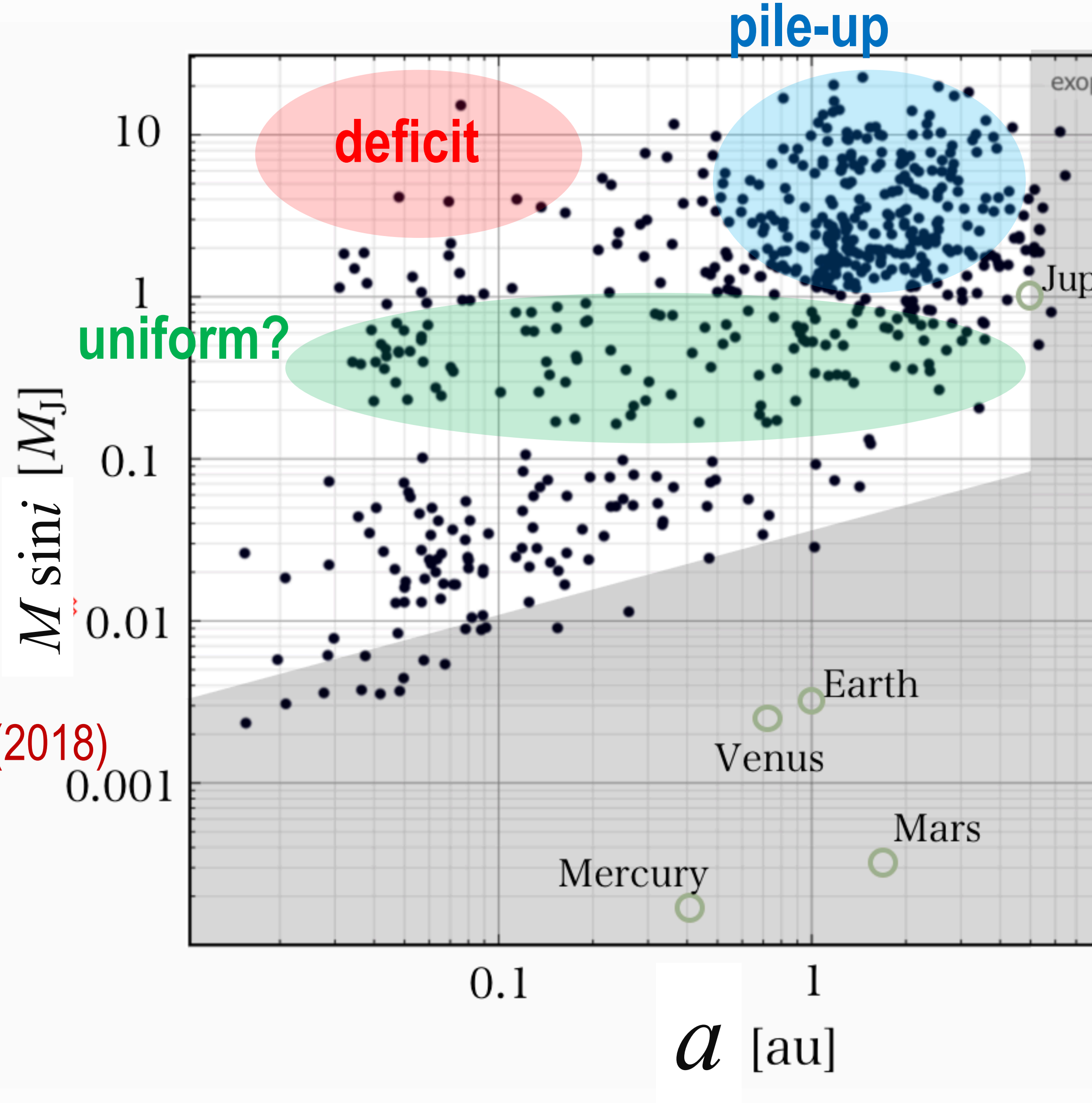


3. disk inner cavity by **internal photoevaporation**

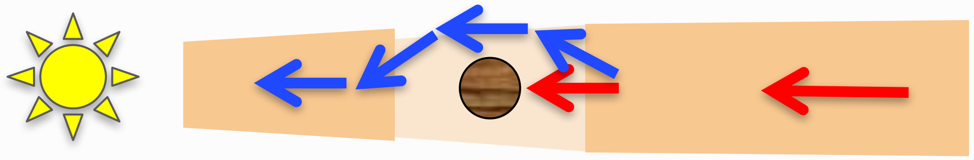
   Alexander & Pascucci (2012), Ercolano & Rosotti (2015), Jennings+(2018)

   → how to explain different a distributions between $M > M_J$ and $M < M_J$?





New type II mig model explains *M-a* distribution of jupiters?

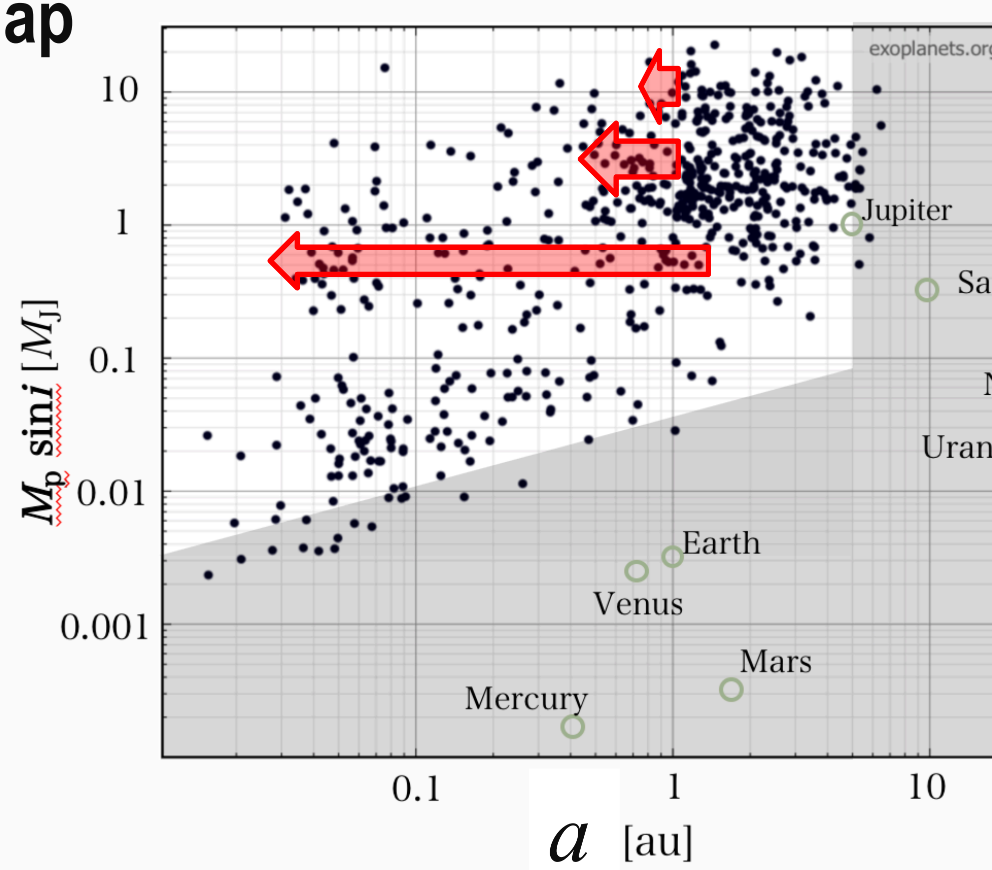


- disk gas passes the gap ← hydro simulations
  Duffell+(2014), Dürmann & Kley (2015), Kanagawa+(2018)

- **type II mig = type I mig with reduced Σ_{gas} in the gap**
  Kanagawa+(2018), Robert+(2018)

- **slow type II migration**
  if turbulent α_{turb} << disk accretion α_{acc}
  - lower α_{turb} → lower Σ_{gas} → slower migration
  - $t_{mig}/t_{dep} \sim (M/M_J)$
    for disk wind (with $\alpha_{turb} \sim 0.1\alpha_{acc}$)

  Ida+(2018)



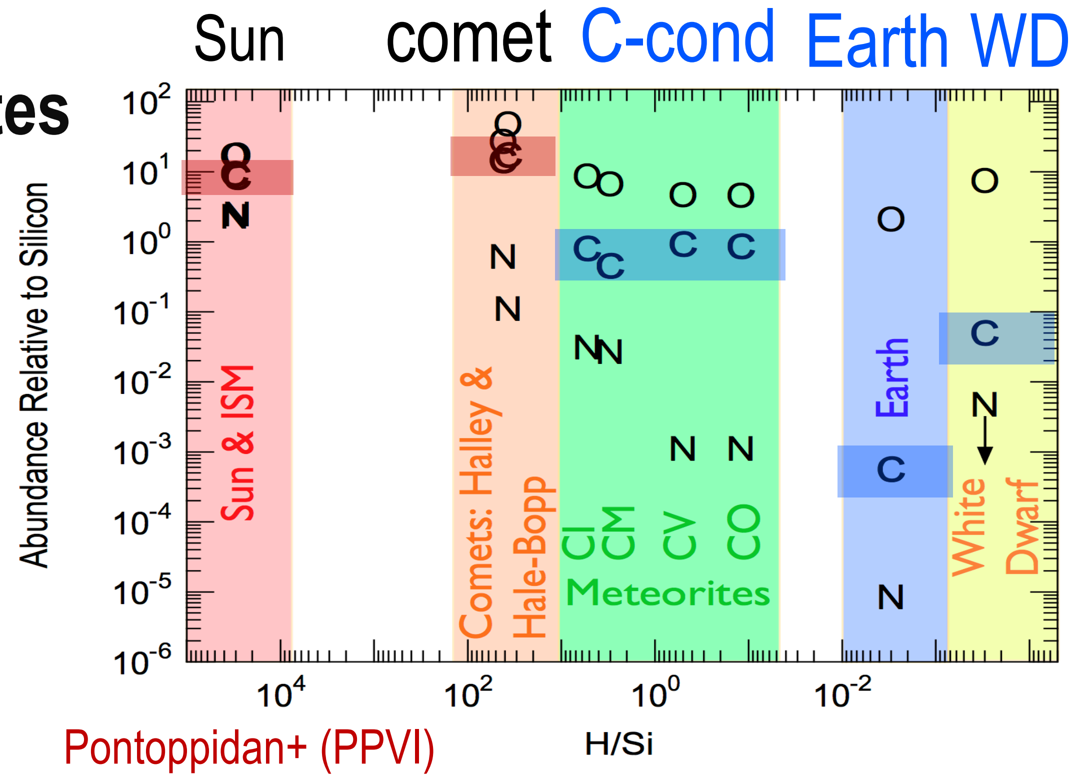
Explain the distr. of jupiters?

ARIEL: constrain type II migration -- C/O of jupiters

- **C/O constrains type II migration history?** Oberg+(2011), Madhusudhan+(2014)
  - ➢ assuming carbon: **half** -- **volatile** forms (CO_2, CO, CH_4 ..)
    + **half** -- interstellar **refractory** carbon (graphite, nano-diamond, large organics ...)

- **Carbon deficit problem**
  - ➢ **Inner Solar system:**
    C is severely depleted – even C-Chondrites
  - ➢ Refractory C: destroyed?
    → changes predicted mig history
    Mordasini+(2016), Cridland+(2019)
  - ➢ How common is the destruction?
    [oxidization by OH? Lee+(2010); **Not clear**]

Carbon deficit problem must be solved

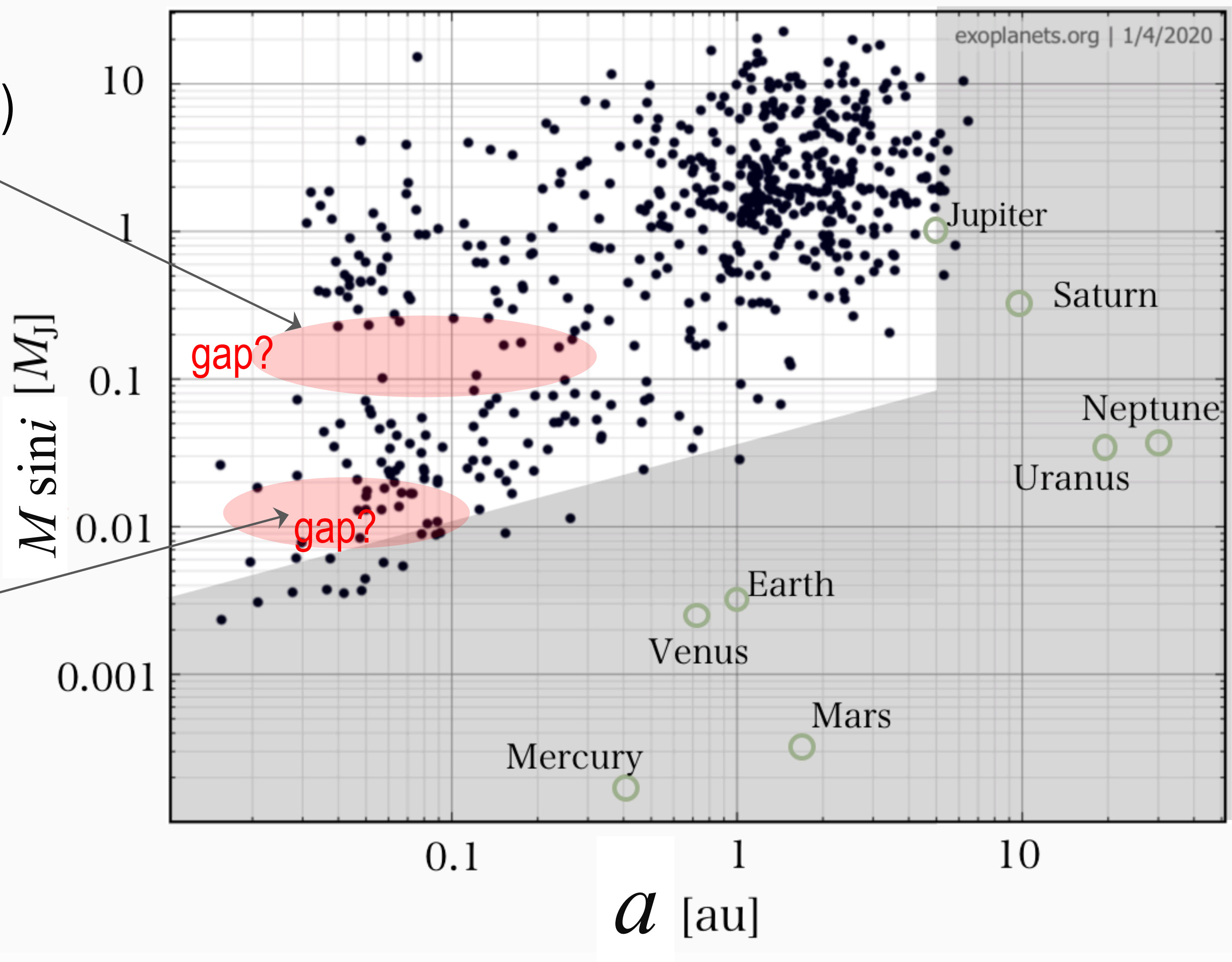


Pontoppidan+ (PPVI)

M-*a* distribution of super-Earths

Predicted by Ida & Lin (2004)
Not clear in Kepler data

Found in Kepler data
Fulton+(2017)

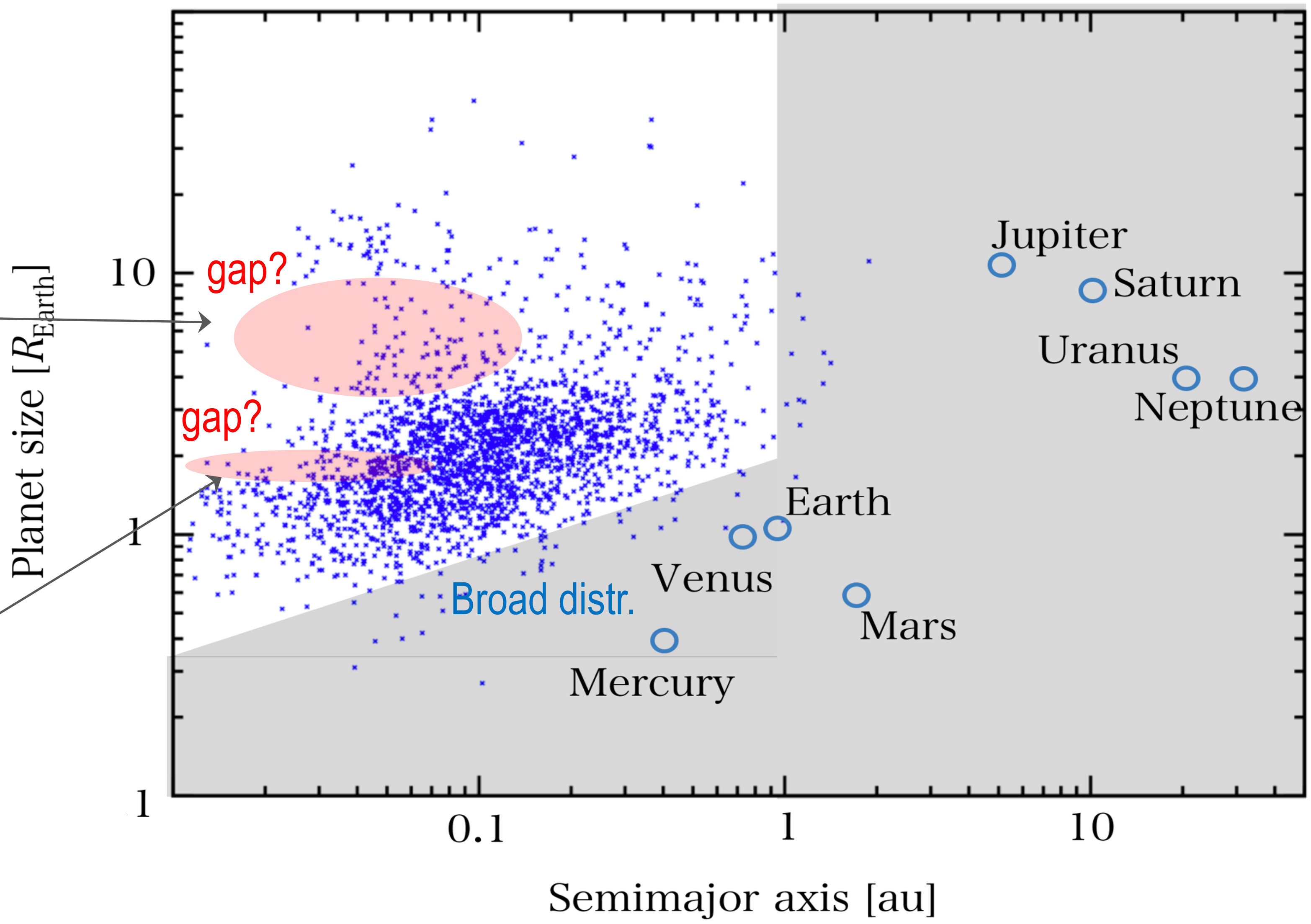


M-a distribution of super-Earths

Kepler data
[only confirmed planets]

Pedicted by Ida & Lin (2004)
Not clear in Kepler data

Found in Kepler data
Fulton+(2017)
atmospheric escape by UV?
Lopez & Rice (2016)

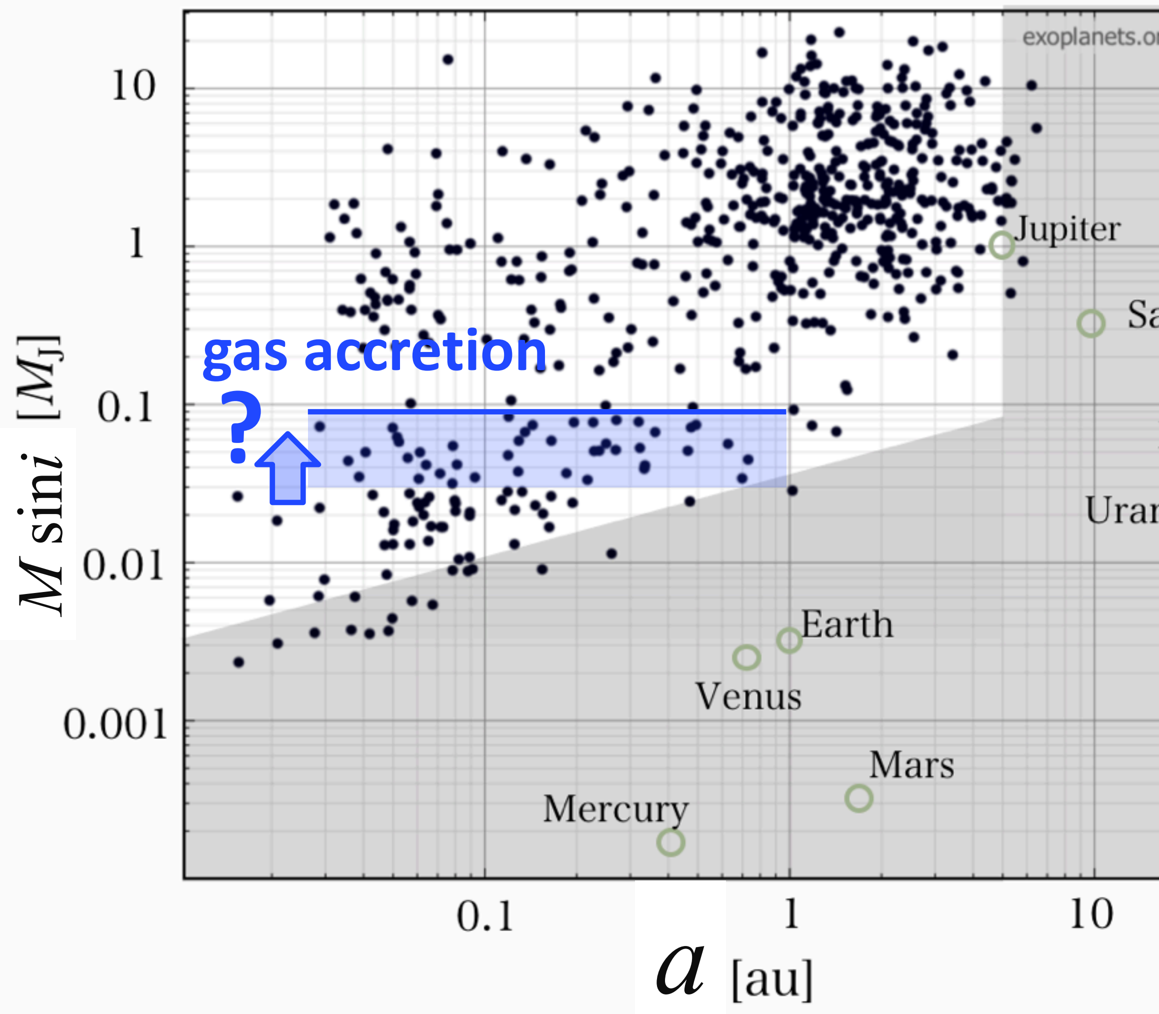


Why super-Earths did not accrete gas to be jupiters?

- $M > M_{crit,core} \sim 10\ M_\oplus$ & small a
  → runway gas accretion?

- Why they did not do that?
  - gap opening? -- not stop gas accretion
    Duffell+(2014), Dürmann & Kley (2015), Kanagawa+(2018)
  - migration of embryos with < a few $M_\oplus$
    + giant impacts after disk gas accretion
    Ida & Lin (2010)
  - atmosphere recycling Ormel+ (2015)

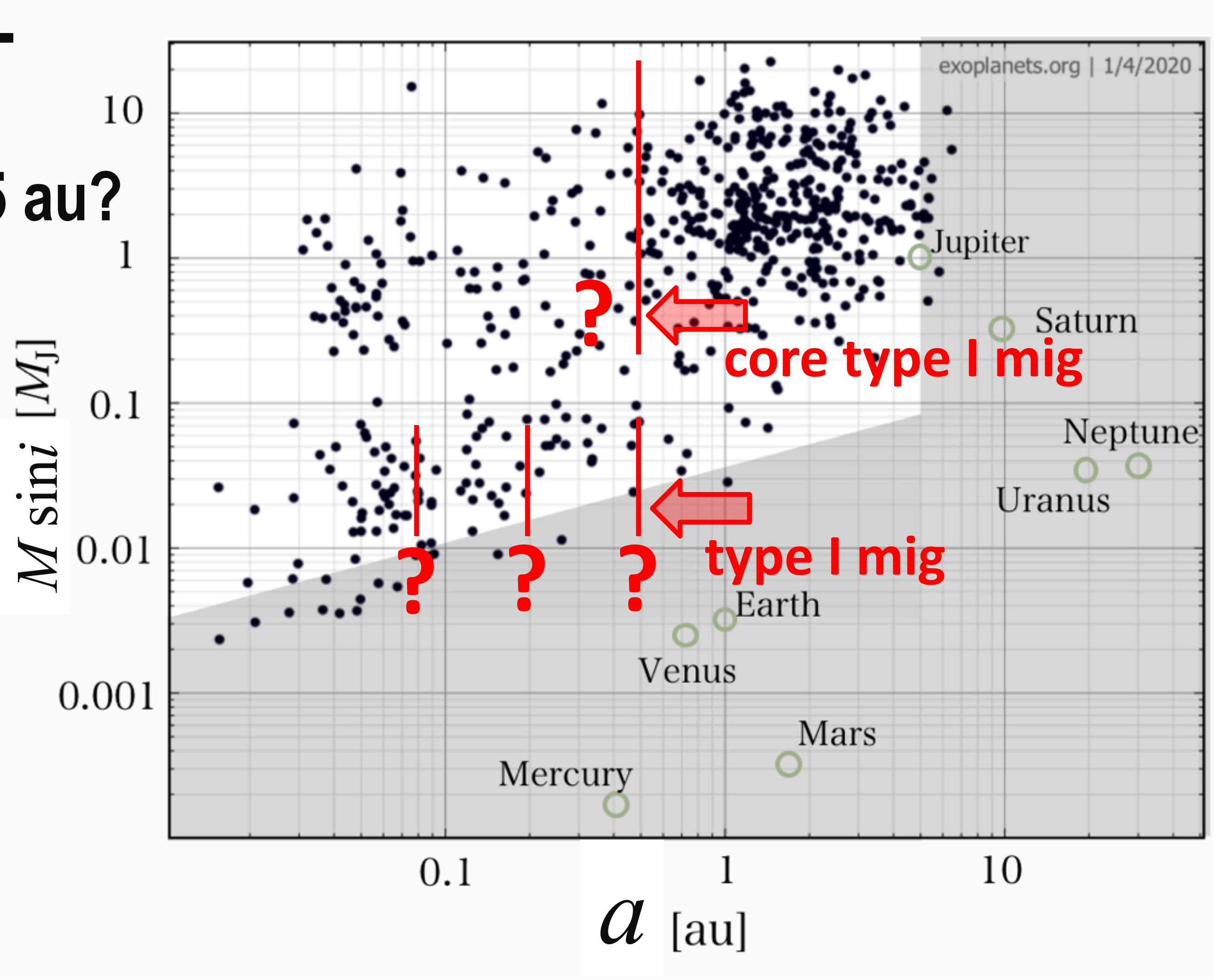
Not clear



Why type I migration of super-Earths were halted?

- How to halt type I migrations of super-Earths in intermediate disk regions?
- How to retain cores of jupiters at > 0.5 au?

- type I migration: many ideas
  - ✓ Non-isothermal
  - ✓ dynamical corotation torque
  - ✓ inner disk depletion by disk wind
  - ✓ pressure bumps
  - ✓ ....



Not clear

ARIEL: diverse atmosphere of super-Earths?

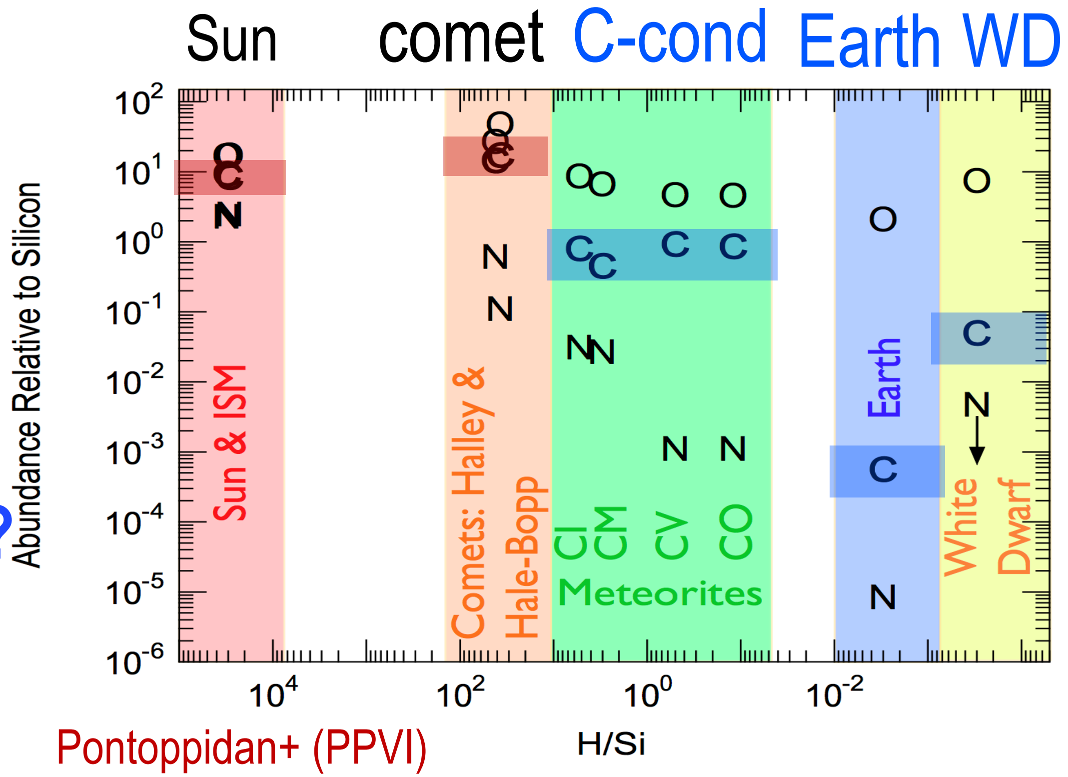
- Formation of close-in super-Earths: still confused
  - ➢ **need constraints from super-Earth atmosphere observation (what data?)**

- **Diverse atmosphere of super-Earths due to refractory carbon destruction?**
  - ➢ Not clear how common is the destruction
  - ➢ **Orders of magnitude variety in carbon abundance may exist among super-Earths**

  → diverse surface environment?

  -- Our on-going project

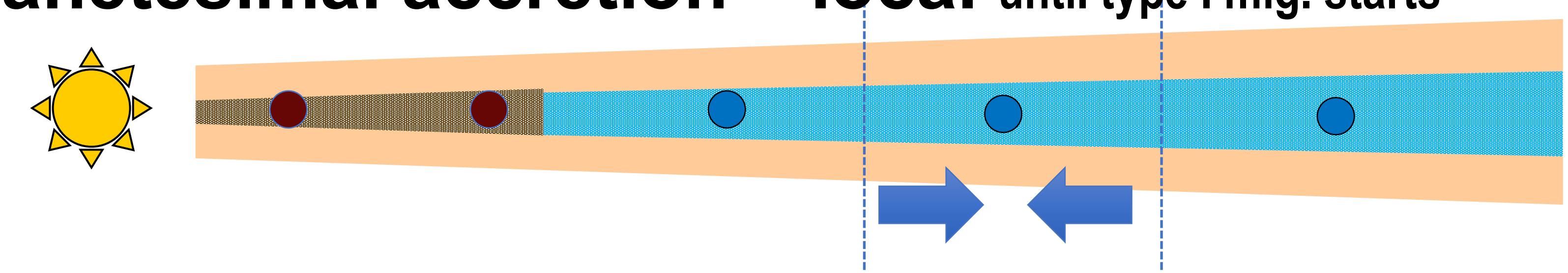
interesting aspect for atmosphere observation?

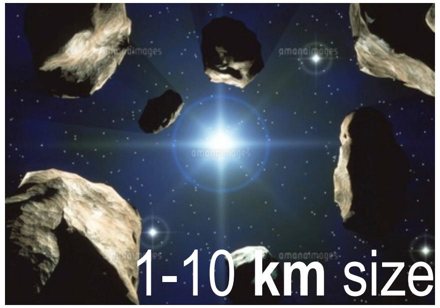


Pontoppidan+ (PPVI)

Pebble accretion

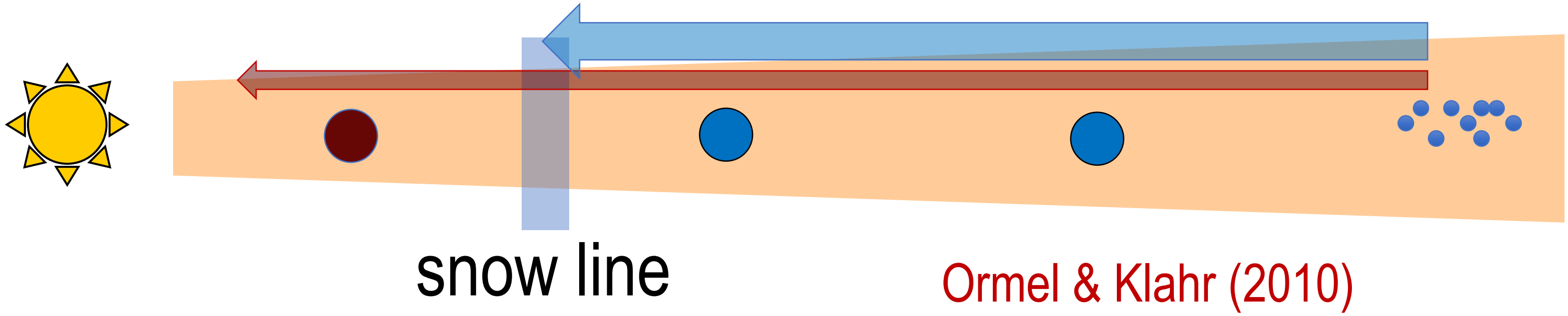
Planetesimal accretion – local until type I mig. starts





Wetherill & Stewart (1989,93)
Kokubo & Ida (1996,98,00,02)

Pebble accretion -- global



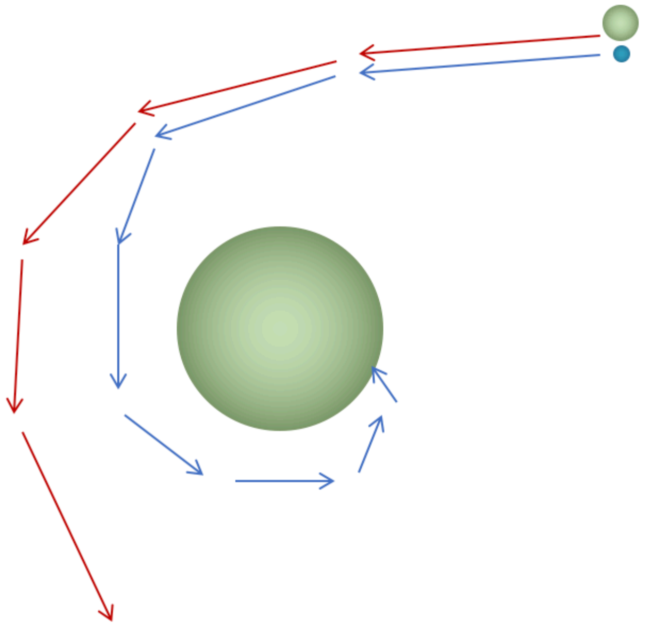
1-100 cm size

Ormel & Klahr (2010)
Lambrechts & Johansen (2012,14a,b)
Levison+(2015)
Guillot, Ida, Ormel (2014)
Ida, Guillot, Morbidelli (2016)

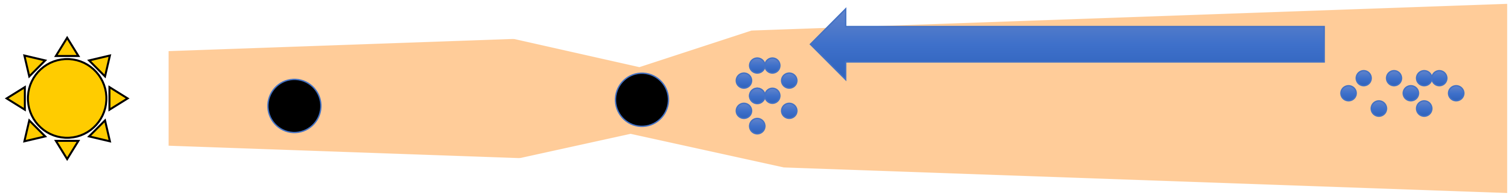
Pebble accretion

Pebble accretion solve the difficulties? NO

- **How to retain cores of jupiters at > 0.5 au?**
  - Rapid enough accretion of cores
    - ✓ Large ($R > 100$km) "seed embryos" are needed
      - **How, Where, When to make them?**
    - ✓ Pebble isolation stops the rapid growth



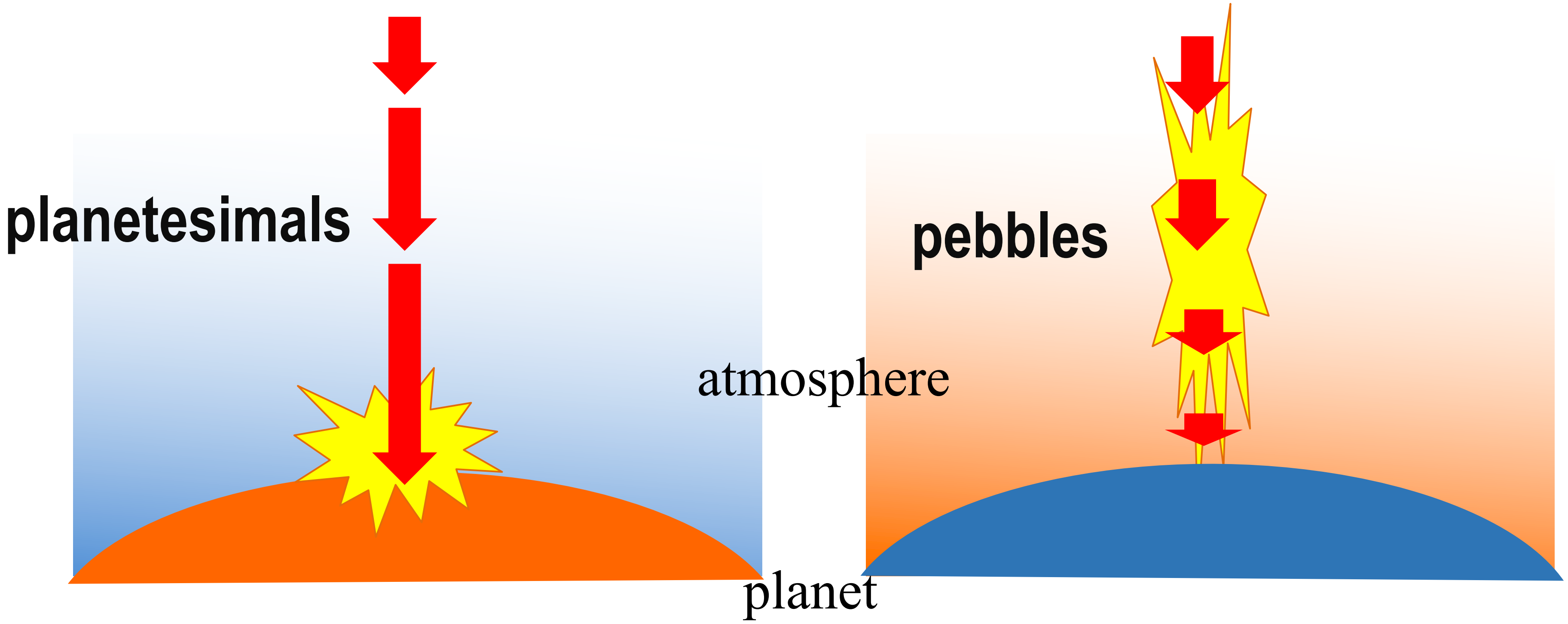
- **Pebble isolation:** accretion stops by a partial gap
  - M_{iso} <~ 10 $M_{\oplus}$ for relatively low α_{turb} → hard to make jupiters
  - jupiter formation prevents formation of close-in super-Earths – inconsistent with observed suggestion?
    Zhu & Wu (2018), Bryan+ (2019)



ARIEL: constrain planetesimals vs. pebbles

- **Magma ocean and resultant atmosphere must be very different**
  - Planetesimal accretion: hit planet surface, giant impacts
  - Pebble accretion: ablated in atmosphere → metal-rich hot atmosphere

Our on-going project



Summary

- **type II migration**
  - New model to explain the distribution of jupiters if $\alpha_{turb} << \alpha_{acc}$.
  - To retrieve **migration history from atmospheric observation, carbon deficit problem must be solved.**
- **type I migration**
  - diverse discussions, not settled down → need observational constraints
  - **orders of magnitude variety of C → diverse surface environment?**
    → tested by atmospheric observation
- **pebble isolation**
  - difficulties: formation of seed embryos? pebble isolation mass?
  - **planetesimal vs. pebble accretion ← constrained by atmospheric observation**